The Fermi Large Area Telescope as a Cosmic-ray detector

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on behalf of the Fermi LAT collaboration

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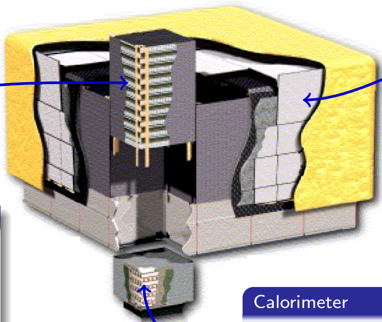
The Large Area Telescope

Large Area telescope

- Overall modular design
- 4×4 array of identical towers (each one including a tracker and a calorimeter module)
- Tracker surrounded by an Anti-Coincidence Detector (ACD)



Tracker

- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis
- 10k sensors, 73 m^2 of silicon active area, 1M readout channels
- High-precision tracking, short dead time

Anti-Coincidence Detector

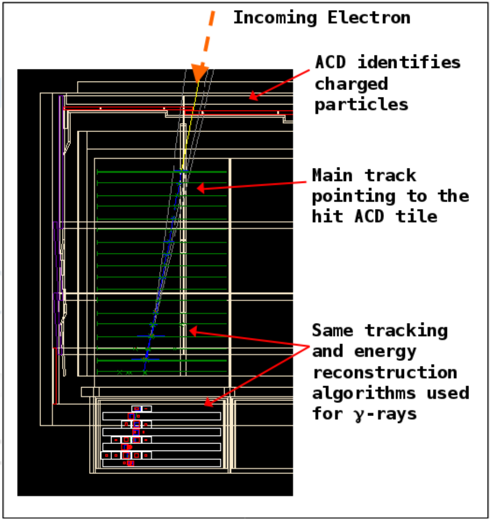
- Segmented (89 tiles) as to minimize self-veto at high energy
- 0.9997 average detection efficiency

Calorimeter

- 1536 CsI(Tl) crystals; 8.6 radiation lengths on-axis
- Hodoscopic, 3D shower profile reconstruction for leakage correction

Not only γ rays

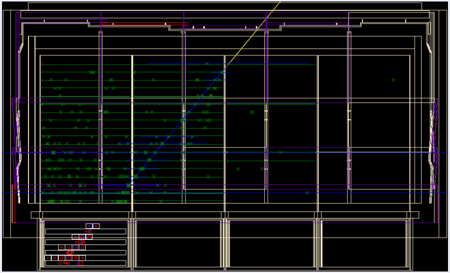
- Detector is designed for E. M. showers
  - Naturally including electrons $(e^+ + e^-)$
- Triggering on (almost) every particle that crosses the LAT
- On-board filtering to remove many charged particles
  - Keeps all events with more than 20 GeV in the CAL
  - Prescaled ($\times$250) unbiased sample of all trigger types
- Event reconstruction assumes a E.M. shower
  - Works fine for electrons
- Electron identification
  - Dedicated event selection
- No charge separation



Electron event selection
Example with flight data

Candidate electron
475 GeV deposited energy, 834 GeV reconstructed

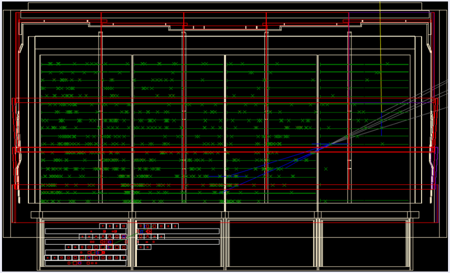
Transverse shower size: 23.2 mm
Fractional extra clusters: 1.48
Average ACD tile energy: 2.46 MeV
Energy reconstruction quality: 0.73



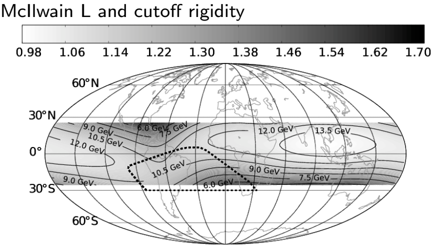
- Clean main track with extra clusters close to the track (note backsplash from the calorimeter)
- Relatively few ACD tile hits, mainly in conjunction with the track
- Well defined (not fully contained) symmetric shower in the calorimeter

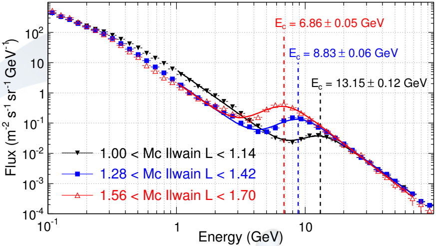
Candidate hadron
823 GeV deposited energy, 1 TeV reconstructed

Transverse shower size: 34.4 mm
Fractional extra clusters: 0.17
Average ACD tile energy: 10.2 MeV
Energy reconstruction quality: 0.15

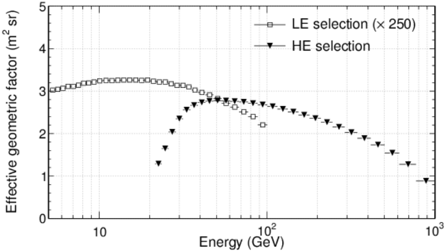


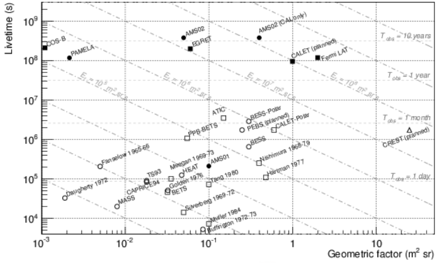
- Small number of extra clusters around main track, many clusters away from the track
- Different backsplash topology, large energy deposit per ACD tile
- Large and asymmetric shower profile in the calorimeter





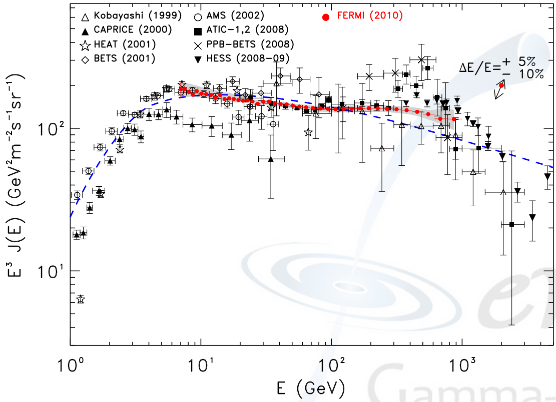
- Data from prescaled on-board filtering
- Different event selection
  - Optimized in this energy range
- Need to take into account the effect of the Geomagnetic field
  - Rigidity cutoff depends on the detector geomagnetic position
  - $\approx$ 7 GeV is the minimum energy accessible in the Fermi orbit
- Data are divided in independent McIlwain L bins
  - The cutoff Energy is extracted by fitting the electron flux
  - For each energy bin only the McIlwain L bins for which the measured cutoff is significantly below the low edge are used





From D.J. Thompson, L. Baldini, Y. Uchiyama arXiv:1201.0988v1

- 2 event selections optimized in different energy ranges
- Peak effective geometry factor of almost 3 m^2 sr around 50 GeV
  - Uncertainty in the absolute effective geometry factor dominates the systematic uncertainties
- Long observation time (continuously running since August 2008)
  - Huge exposure
- The estimated hadronic contamination is below ≈20%
  - Subtracted from the candidate electron sample

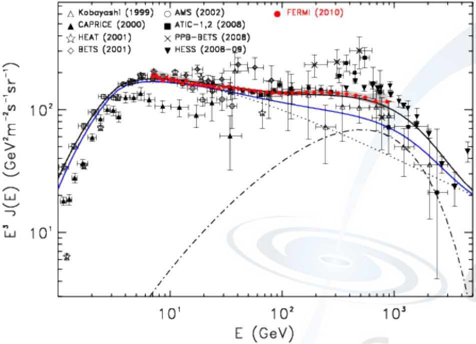


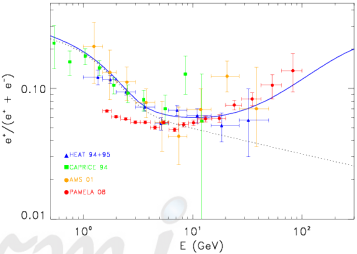
Details in:

- Phys. Rev. Lett. 102, 181101 (2009)
- Phys. Rev. D 82, 092004 (2010)

- Systematics limited spectrum from 7 GeV to 1 TeV
- Spectrum is harder than in pre-Fermi GALPROP model
  - Best fit with a single power-law gives $\Gamma \sim 3.08$
- Diffusive models don't reproduce spectral features

Local (?) Extra component ?





From D.Grasso et al. Astropart. Phys. 32, 140-151 (2009)

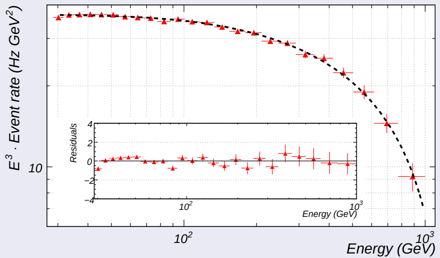
- Adding an extra component nicely fits the Fermi spectrum
  - Together with PAMELA positron fraction
- Several possibilities for an additional source of e^+/e^-
  - Either astrophysical or exotic (or both)

Alternative event selection

Optimized for energy resolution

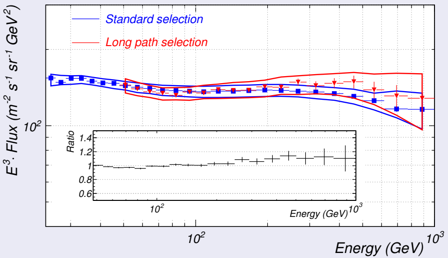
- Events with long path (13 X_0 min, 16 X_0 average) in the instrument and contained in a single calorimeter module
  - Energy dispersion much narrower and more symmetric, energy resolution better than 5% (1σ) up to 1 TeV
  - Acceptance reduced to 5% of the standard one

Event rate



- No evidence of any significant spectral feature
- Dashed line is a fit with a smooth function

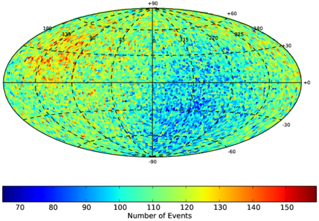
Spectrum



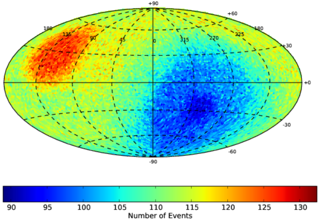
- The two spectra are consistent within the systematic errors
- Long path selection has larger systematic errors
  - A cross check, not necessarily more accurate

Fermi offers a unique opportunity for the measurement of possible anisotropies (large exposure and complete sky coverage)

Count map (E $>$ 60 GeV)

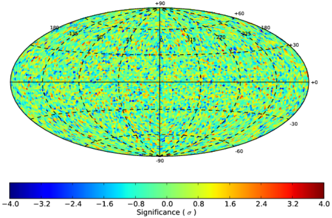


No-anisotropy map (E $>$ 60 GeV)



- Comparison of the real sky map with *no-anisotropy* one (null hypothesis case)
  - Accounts for non uniform exposure
  - Constructed artificially from the actual data set
  - Two different methods

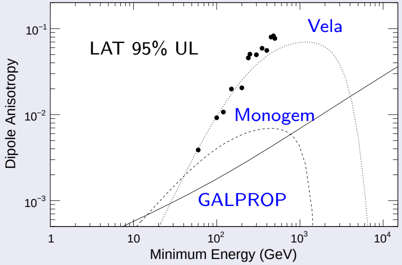
Significance map (E $>$ 60 GeV)



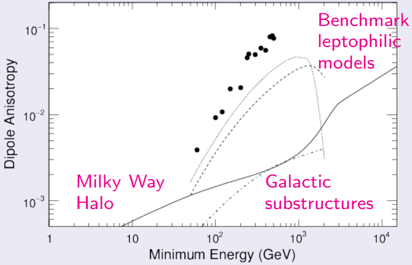
Search for anisotropies in $e^- + e^+$

- No anisotropy observed: upper limits
- Dipole anisotropy is a valuable tool to constrain models
  - 95% confidence level compared with several models
  - Dominance of a single, very bright nearby source is disfavored
  - Dark Matter models predict a smaller effect

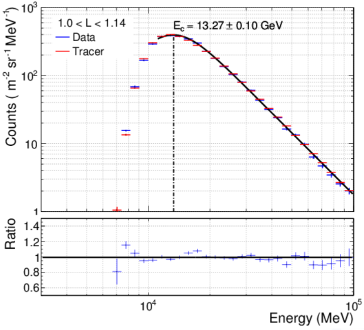
Astrophysical sources

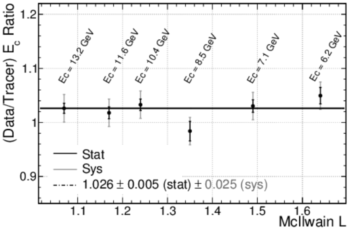


Dark Matter models



Details in: Phys. Rev. D 82, 092003 (2010)



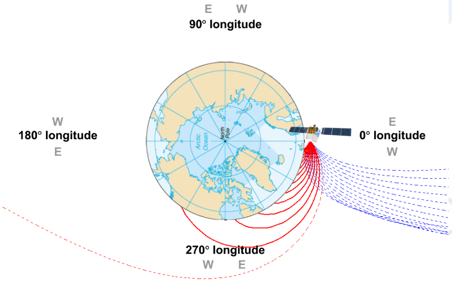


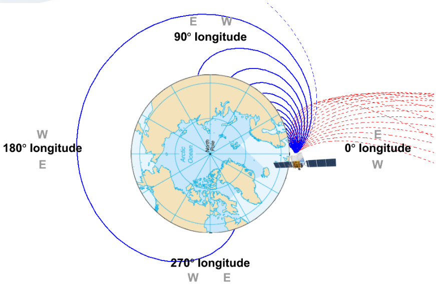
- The value for the cutoff rigidity can be predicted using a particle tracing code
  - Using code written by Smart & Shea (Final Report, Grant NAG5-8009, 2000)
  - Cross checks on the fidelity of the geomagnetic field model have been performed using rigidity measurements from other satellites such as SAMPEX and HEAO-3
- Comparison of predicted and measured values provides an opportunity to perform an in-fight verification
- By using different McIlwain L intervals we obtain several calibration points from 6 to 13 GeV
  - The energy scale is known within 5% (in this energy range)

Details in: Astropart. Phys., 35, 346 (2012)

How we can distinguish e^+ and e^-

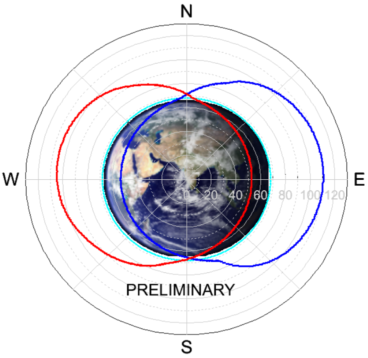
- The LAT doesn't carry a magnet on-board
  - We can not directly discriminate particle charge
- The only magnet we can use is provided by the Earth





- The solid Earth surrounded by its magnetic field blocks some of the particle trajectories
  - Continuous lines in the figures above
- There are regions in which only one of the two particle types is permitted
  - Pure e^+ region in the West direction
  - Pure e^- region in the East direction

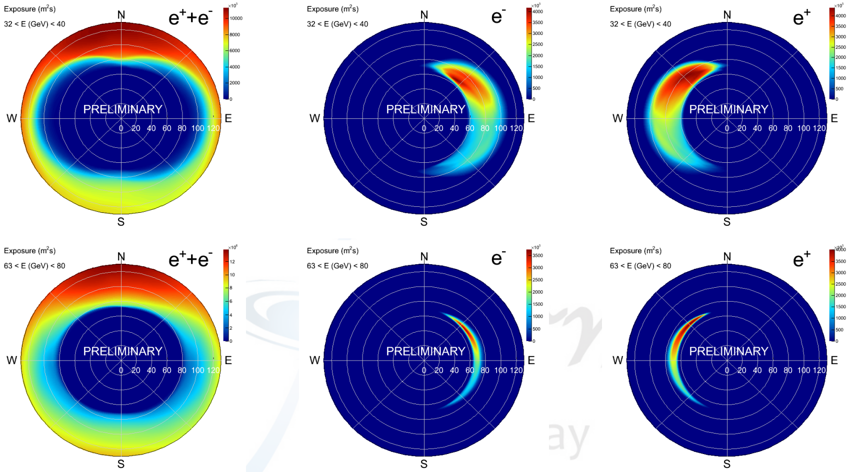
Identify e^--only and e^+-only regions



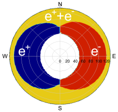
Example of region boundary for one real event:

- e^+ are forbidden inside blue curve
- e^- are forbidden inside red curve

- We find the curve that separates permitted from forbidden part of the sky
  - In Earth-centered coordinate system
  - Assuming e^- and e^+ separately
- Particle trajectories are numerically traced in geomagnetic field
- Region boundaries vary with energy and LAT position in the orbit
  - They are calculated for each event



- Three regions used in this analysis: $e^+ + e^-$, e^-, e^+
  - Smaller e^-–only and e^+–only as energy increases
- Useful data only when the LAT is looking down at the Earth
  - ∼39 days of livetime, up to April 2011, taken in non–survey mode



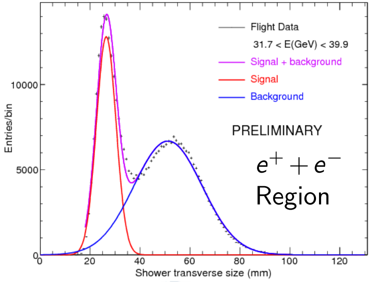
- Main background is residual CR proton
- Up to ~60% in e^+ after event selection

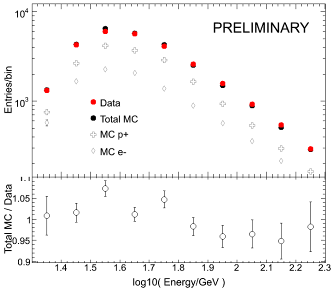
Fit-Based Method

Fit the distributions of transverse shower size in the CAL with 2 Gaussians to determine signal

MC-Based Method

Apply event selection to a large set of proton Monte Carlo simulations to estimate surviving background

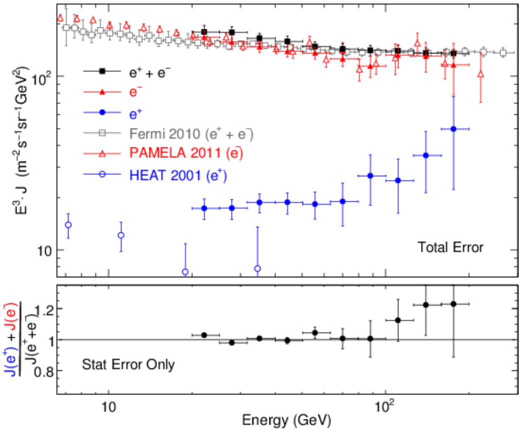




$e^+ + e^-$ Region

One selection criterion inverted

Cosmic-ray e^+-only and e^--only spectra



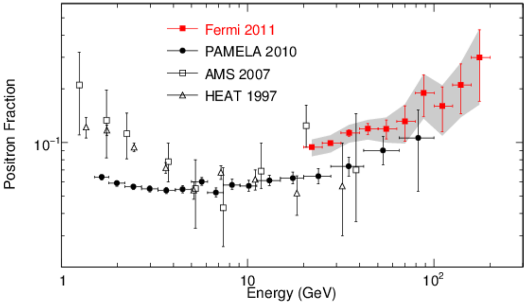
Fit with power law, spectral indices:

2.77 ± 0.14 for e^+

3.19 ± 0.07 for e^-

- Use Fit-based results up to 160 GeV, where statistics are not enough for the fitting procedure, and use MC-based results above 160 GeV
- Results from two methods are consistent within errors
- Bottom panel shows that ratio of the sum $J(e^+) + J(e^-)$ to $J(e^+ + e^-)$ is consistent with 1

Positron Fraction



- Derived from e^+ and e^- spectra
  - We don't use the both-allowed region except as a cross check
- Positron fraction increases with energy from 20 to 200 GeV
  - As observed by PAMELA

Details in Phys. Rev. Lett. 108, 011103 (2012)

Conclusions

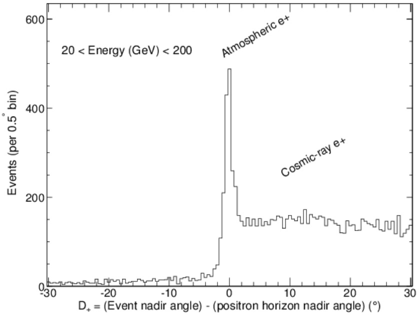
- Cosmic-ray studies with the Fermi-LAT have been quite successful:
  - Inclusive $e^- + e^+$ spectrum from 7 GeV to 1 TeV
    - Systematics-limited measurement
    - Covering almost 2.5 decades in energy
  - Search for anisotropies in the arrival directions above 60 GeV
    - Upper limits ($< 1\%$ to a few %, depending on the energy threshold/angular scale) are already interesting in terms of modeling
    - Will improve as more data are collected
  - Cosmic-ray e^+-only and e^--only spectra between 20–200 GeV
    - Using the Earth's magnetic field as charge discriminator
    - The positron fraction derived from this measurement confirms the behavior already observed by PAMELA
- Not the end of the story
  - Increasing statistics
    - The Fermi-LAT is still taking data flawlessly
  - Improving event reconstruction
    - Extending energy range to a few TeV
    - Better control of systematic effects

EXTRA

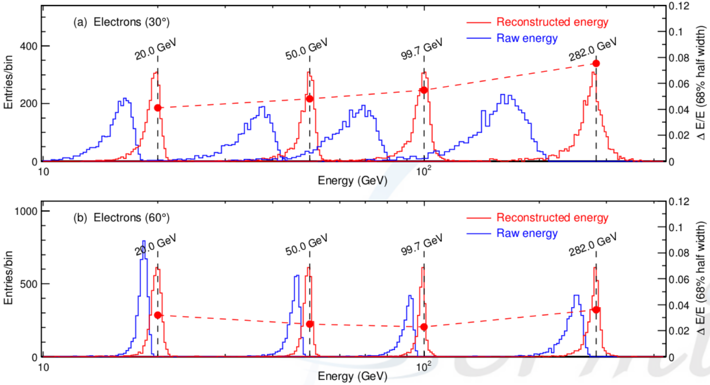
Atmospheric emission

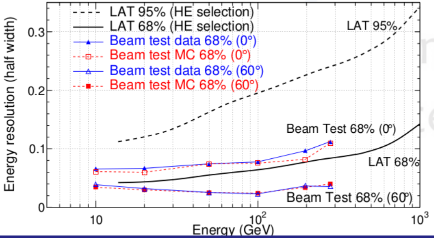
- Region boundaries correspond to location of atmospheric secondary emission
  - CR interacting in the Atmosphere
  - Same mechanism as γ-ray limb
- Atmospheric particle peak observed where expected
  - Good check of region selection algorithm

- A cut (vertical line) is applied to remove atmospheric particles
  - 4° cut up to 100 GeV and 2° above
  - Some effect only for e^+
  - Estimated residual contamination included in systematics



Energy Reconstruction





Energy reconstruction

- Same algorithms used for the γ analysis.
- Validated with electron beams at CERN.
- The excellent data/MC agreement gives us solid ground in extrapolating to 1 TeV.
- 5–15% (20 GeV–1 TeV, 1 σ) for an isotropic flux, after the electron cuts.